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GAMMA RAYS AND NEUTRONS FROM A LARGE SOLAR FLARE ON NOVEMBER 6, 1997

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ABSTRACT

Yohkoh observed a large solar flare (X9/2B) on November 6, 1997. The flare showed strong gamma-ray emission between 11:52 and 11:56 UT (peak phase) and several gamma-ray lines were detected. After 11:56 UT a weak and extended gamma-ray emission was measured. The ratio of Mg+Si+Fe to C+O+Ne line fluxes was enhanced by a factor of about three in the extended phase. The Oriented Scintillation Spectrometer Experiment (*OSSE*) on board the Compton Gamma-Ray Observatory (CGRO) detected significant neutrons associated with the flare between 12:08 and 12:30 UT. The observed neutron count-rate time profile suggests that neutrons originated in interactions that occurred in both peak and extended phases.

INTRODUCTION

A large solar flare produces gamma rays and neutrons which provide direct evidence for high-energy ion production during solar flares (Chupp *et al.*, 1990; Murphy *et al.*, 1999). Particle acceleration time, energy spectrum, directivity and ambient and accelerated elemental abundances have been studied from detailed analyses of gamma-ray line spectra and neutron arrival times (Chupp *et al.*, 1987; Ramaty *et al.*, 1996; Mandzhavidze *et al.* ,1997; Murphy *et al.* ,1997, 1999 and Share and Murphy, 2000). In this paper we review *Yohkoh* gamma-ray and *CGRO*/OSSE neutron observations from the 1997 November 6 flare. The gamma-ray flare was observed with *Yohkoh* and neutrons were detected with the *OSSE* after the gamma-ray flare was over. The temporal variation of a gamma-ray line flux ratio is discussed. In order to explain the observed neutron time profile, we examine the timing of the neutron production from the *Yohkoh* and *OSSE* data.

GAMMA-RAY AND NEUTRON OBSERVATIONS

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The *Yohkoh* gamma-ray spectrometer measured a large gamma-ray flare at 11:52 UT on 6 November, 1997. Its *GOES* class, Hα importance and location were X9.4, 2B and S18W63, respectively. This flare was the most intense gamma-ray event which *Yohkoh* has recorded up to date and high-energy gamma rays of more than a few tens of MeV were measured (Yoshimori *et al.*, 2000a). The gamma-ray emission was impulsive and lasted for about 4 minutes. The background-subtracted emission at 4-7 MeV is shown in Fig. 1. Gamma rays at 4-7 MeV are dominated by the C (4.44 MeV) and O (6.13 MeV) lines. The gamma-ray flare starts at 11:52:30 UT, reaches a peak at 11:53:40 UT and falls with a decay constant of about 50 s. However, we see a weak and extended emission at 4-7 MeV after the strong gamma-ray emission was over. The background-subtracted gamma-ray count spectrum over 11:52:48-12:01:52 UT (flare-averaged spectrum) is shown in Fig. 2. We see the 2.22 MeV

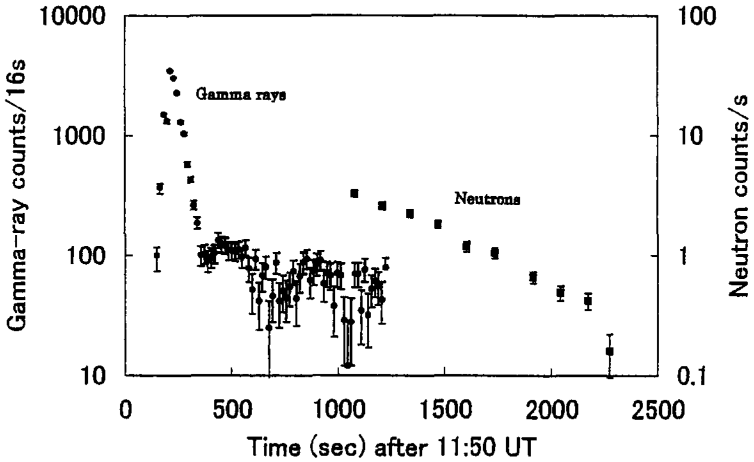

Fig. 1 Time profiles of background-subtracted gamma rays (4-7MeV) and neutrons (energy loss of >16 MeV)

line, de-excitation C and O lines and a complex of Ne, Mg, Si and Fe lines in the 1.1-1.8 MeV band. The gamma-ray count spectra in 11:53:24-11:54:16 UT and 11:54:16-12:01:52 UT are given in Fig. 3 (a) and 3(b). The bremsstrahlung flux is significantly strong in the first period, while the Mg+Si+Fe lines between 1.1-1.8 MeV are apparent in the second period. The time variation in the ratio of >1MeV bremsstrahlung to C+O+Ne narrow line fluxes is shown in Fig. 4. We find that the ratio decreases in the second period.

The *OSSE* instrument consists of four independently oriented NaI scintillation detectors. Both gamma rays and neutrons are distinguished by a pulse shape discrimination method (Share *et al.*, 1978). Using the instrumental response functions for gamma rays and neutrons, we derive their energies from the energy-loss spectra. Neutrons of 36-100 MeV and gamma rays of 15-65 MeV can be well separated but the pulse shape discrimination method is not reliable at high energies. The *OSSE* missed the flare because it was in the SAA before 12:08 UT. The *OSSE* observed the Sun between 12:08 and 12:30 UT (The night time started at 12:30 UT). The count-rate time profile of neutrons of energy loss of >16 MeV is shown in Fig. 1 along with the 4-7 MeV gamma rays. The neutron count

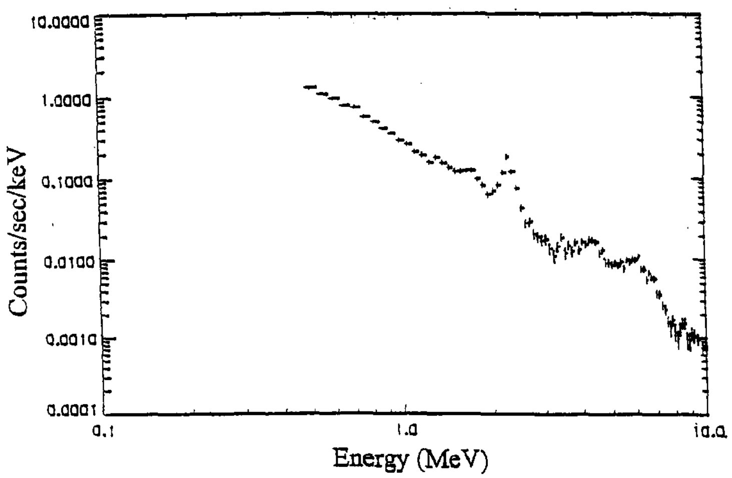

Fig.2 Flare-averaged gamma-ray count spectrum over 11:52:48-12:01:15 UT

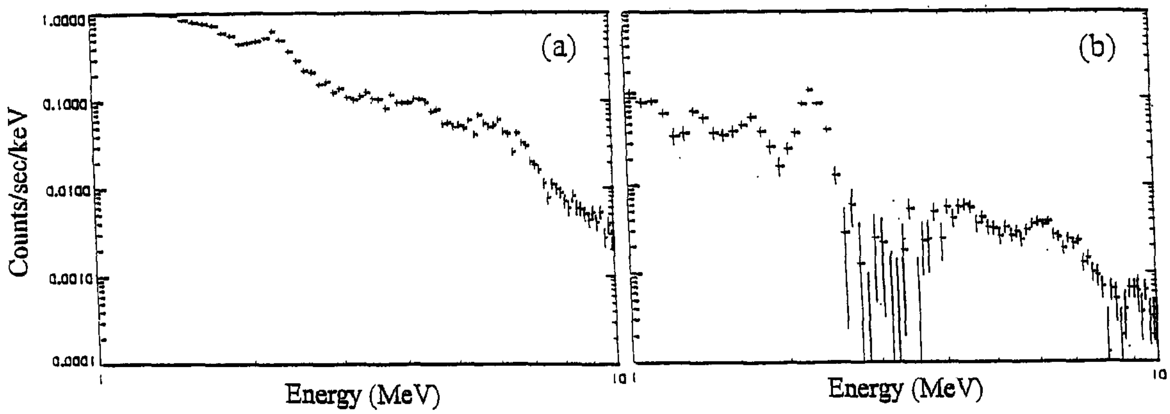

Fig. 3 Gamma-ray count spectra in (a) 11:53:24-11:54:16 UT and (b) 11:54:16-12:01:52 UT

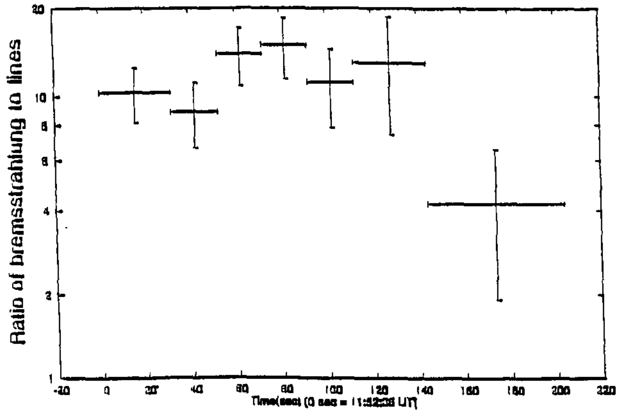

Fig.4 Time variation in the ratio of > 1MeV bremsstrahlung to C+O+Ne line fluxes

rate decreased with time. When the *OSSE* passed a region of similar background condition in both previous and subsequent orbits, the *OSSE* did not record a change in the count rate. Moreover, we plot the separated neutrons and gamma-ray energy loss spectra between 12:08 and 12:30 UT in Fig. 5. The *OSSE* result indicates that the measured events are predominantly due to solar neutrons.

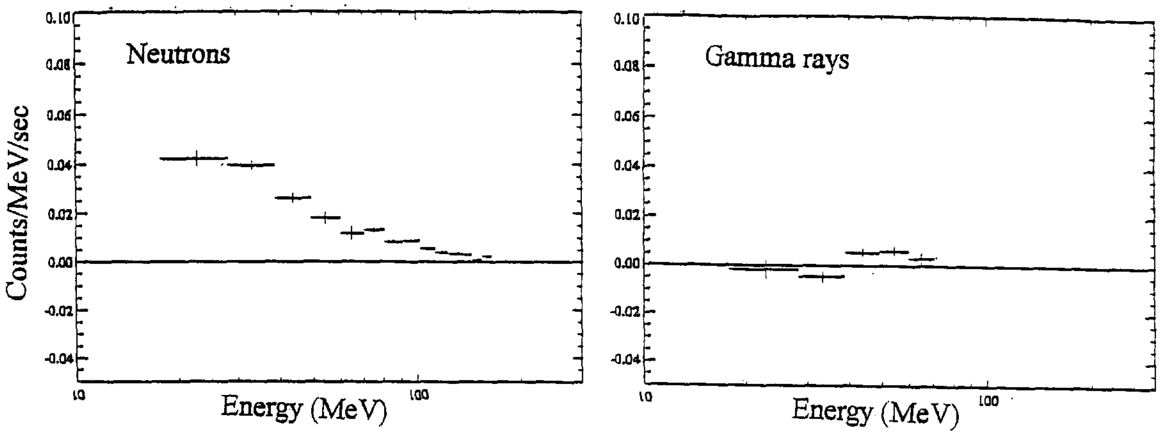

Fig. 5 Energy-loss spectra of separated neutrons (16-150 MeV) and gamma rays (15-65 MeV)

DISCUSSION

The ratio of Mg+Si+Fe to C+O+Ne line emissions is enhanced by a factor of 2.7±0.5 in the extended phases. It suggests that the relative abundances of ambient low-FIP elements (Mg, Si and Fe) at the gamma-ray emission site increased in the late phase. The *Yohkoh* result suggests the possibility that the ambient low-FIP elements were efficiently transported to the chromosphere or the gamma-ray production site moved from the chromosphere to the corona (low-FIP element abundances in the corona are about three times as large as that in the chromosphere). A similar temporal variation was reported from the 1991 June 4 flare (Murphy *et al.*, 1997). Since the bremsstrahlung flux is significantly high in the first period, the gamma-ray line features are not clearly seen. On the other hand, the gamma-ray flux at 3 MeV (bremsstrahlung is dominant) decreased in the second period. It leads to the decrease in the ratio of bremsstrahlung to line emissions in the second period (see Fig. 4).

Here we try to explain the observed neutron arrival time profile shown in Fig. 1. Assuming that neutrons are produced in a very short time, Murphy and Ramaty (1984) calculated the neutron time profile at the Earth for certain spectral indices of accelerated protons. If the neutron production rate is given as a function of time, we can get the resultant neutron time profile at the Earth. Strong 4-7 MeV emission was observed in the first four minutes (peak phase) but after that the weak emission lasted for ten minutes (extended phase). The time profile of neutron production rate is estimated from the observed time profile of gamma-ray lines for certain proton spectral indices

(Ramaty and Murphy, 1987). First we show the calculated neutron time profiles at the Earth for the proton spectral indices of 3, 4 and 5 in Fig. 6. The calculated ones are not consistent with the observed data. It seems to be difficult to explain the *OSSE* neutron data as far as we consider the constant proton spectral index during the flare. Next, we consider the possibility that the proton spectral index varies with time. For simplicity, the spectral index in the peak phase is different from that in the extended phase. Assuming that the proton spectral index is 3.5 in the peak phase and 3.0 in the extended phase, we plot the calculated neutron time profile in Fig. 7. Here the total numbers of protons above 30 MeV are 1.05 x 10^{33} and 2.95 x 10^{31} for the peak and extended phases, respectively. The calculated time profile is in agreement with the observed one within the experimental errors. This result suggests that the proton spectral hardening occurred in the extended phase. The proton spectral index

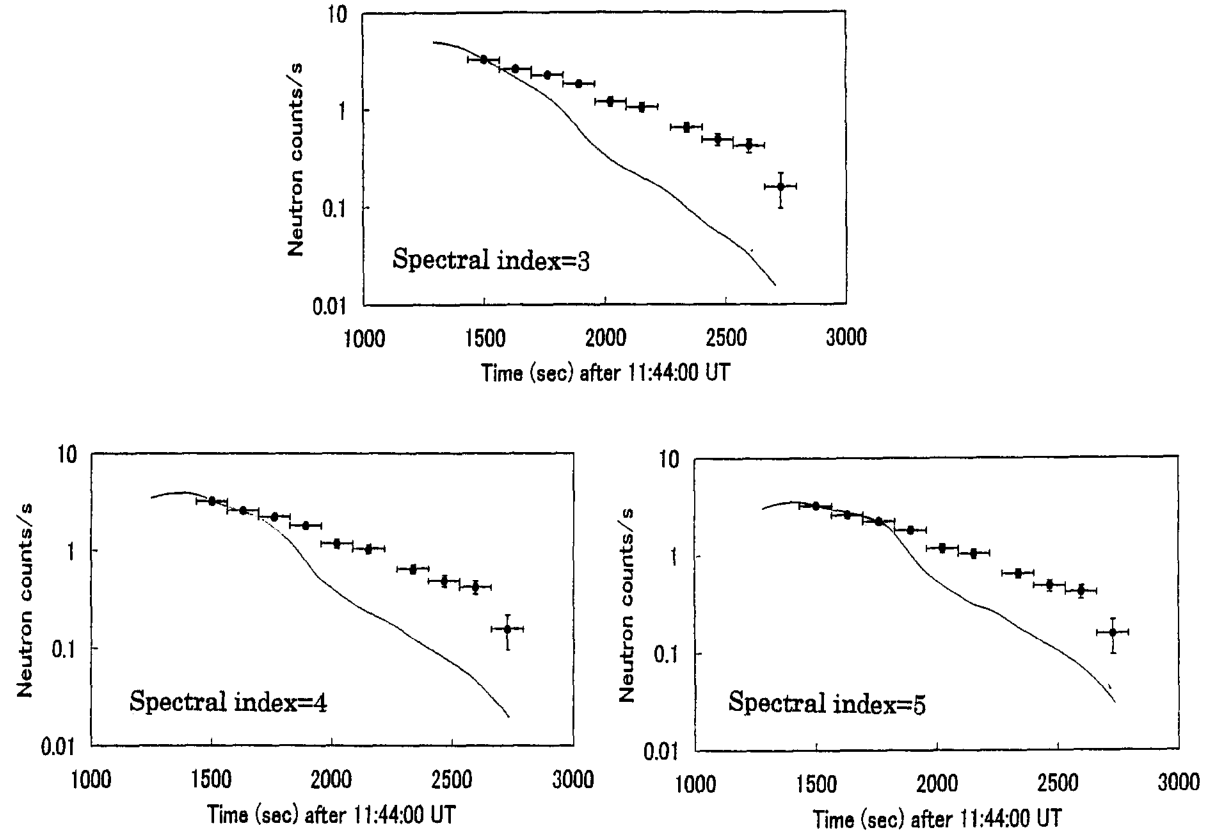

Fig. 6 Comparison of the calculated neutron time profile with the observed one. The proton spectral indices are assumed to be 3 ,4 and 5 and are constant during the flare.

is derived from a ratio of the neutron-capture line to the C and O line fluxes. It is 3.0-3.5 in the peak phase (Yoshimori *et al.*, 2000b). The present assumption of spectral index of 3.0- 3.5 is reasonable with the Yohkoh gamma-ray observation.

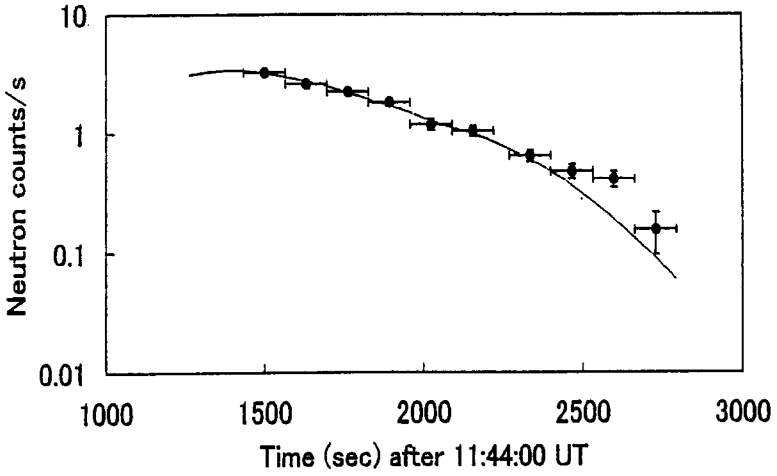

Fig. 7 Comparison of the calculated neutron time profile with the observed one. The spectral index is assumed to be 3.5 in the peak phase and 3.0 in the extended phase.

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